Accurate Wind Farm Development and Operation
Advanced Wake Modelling

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PO. 233

Industry Needs

Reduction of the Cost of Energy

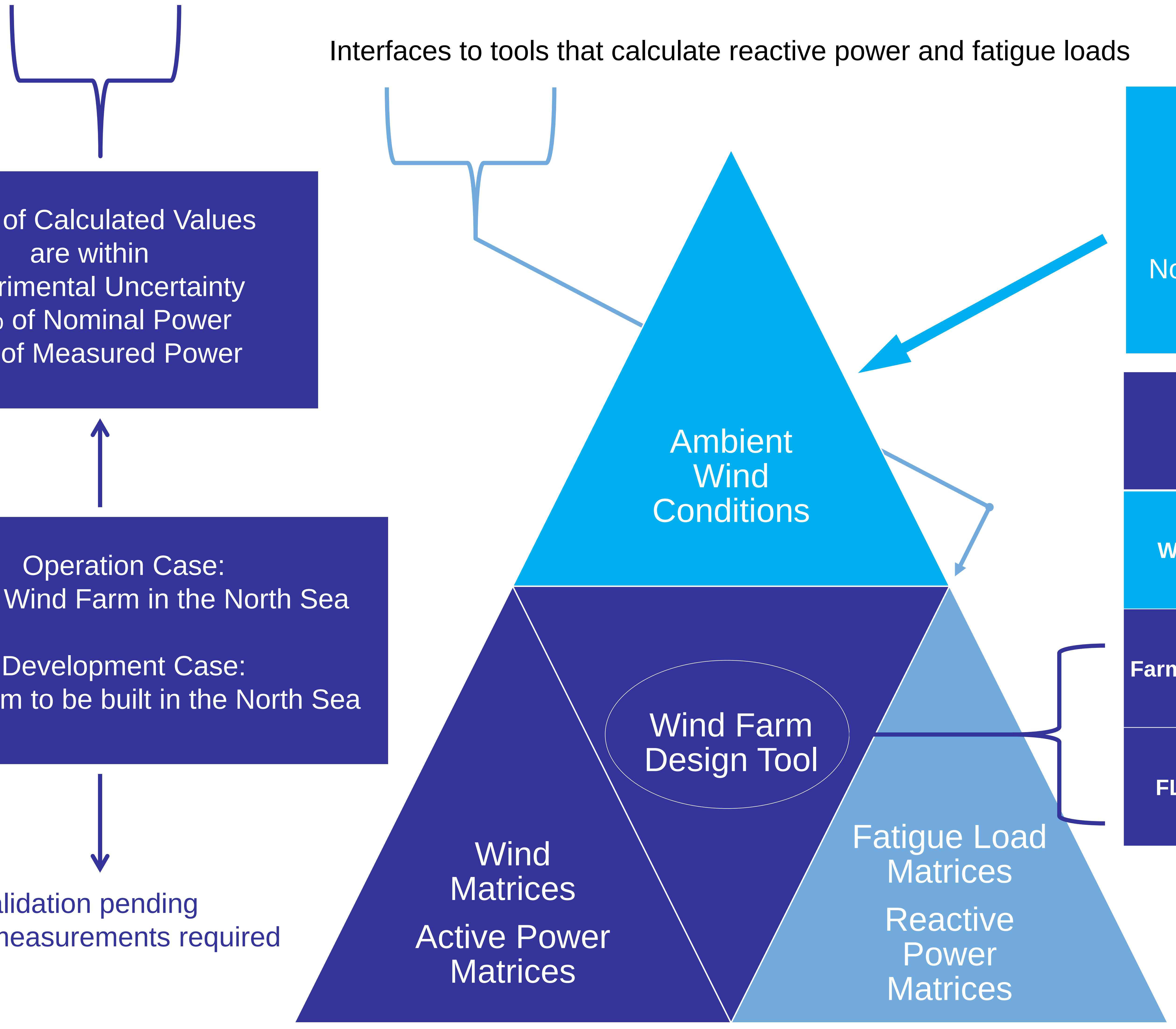
Accurate Calculation of Electrical Power and Fatigue Loads
Wind Farm Cluster Control Capabilities

Our Solutions

Wind Farm Design Tools for Development and Operation

Accurate calculation of wind speed, turbulence intensity, vertical wind shear and active power in clusters of wind turbines

Interfaces to tools that calculate reactive power and fatigue loads



>80% of Calculated Values
are within
Experimental Uncertainty
±3% of Nominal Power
±3% of Measured Power

Operation Case:
Existing Wind Farm in the North Sea

Development Case:
Wind Farm to be built in the North Sea

Validation pending
Further measurements required

Ambient Wind Conditions

Wind Farm Design Tool

Wind Matrices

Active Power Matrices

Fatigue Load Matrices

Reactive Power Matrices

Real-live Met Mast

Numerical WRF Met Mast

No significant differences in power calculations

	Wind Farm Internal Wakes	Wakes Between Wind Farms	Ambient Wind
WRF	x	V	V
FarmFlow	V	V	x
FLaP	V	x	x

Acknowledgements

FP7-ENERGY-2011 283145 / ClusterDesign

References

www.cluster-design.eu
Deliverable 1.4: Coupled wind farm wake and wind turbine wake models
Deliverable 1.5: Results of benchmarking test
Deliverable 3.4: Analytical validation report – loads and performance
Deliverable 6.1: Validation report

Poster presentation by RWE Innogy, PO 257
Oral presentation by REpower Systems SE, Thu 21 Nov 2013, 11:00-12:30

OFFSHORE 2013
FRANKFURT
ORGANISED BY EWEA
19-21 NOVEMBER

Accurate wind farm development and operation - Advanced wake modelling

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Summary The ability is demonstrated to calculate wind farm wakes on the basis of ambient conditions that were calculated with an atmospheric model. Specifically, comparisons are described between predicted and observed ambient conditions, and between power predictions from three wind farm wake models and power measurements, for a single and a double wake situation. The comparisons are based on performance indicators and test criteria, with the objective to determine the percentage of predictions that fall within a given range about the observed value. The Alpha Ventus site is considered, which consists of a wind farm with the same name and the met mast FINO1. Data from the 6 REpower wind turbines and the FINO1 met mast were employed. The atmospheric model WRF predicted the ambient conditions at the location and the measurement heights of the FINO1 mast. May the predictability of the wind speed and the wind direction be reasonable if sufficiently sized tolerances are employed, it is fairly impossible to predict the ambient turbulence intensity and vertical shear. Three wind farm wake models predicted the individual turbine powers: FLaP-Jensen and FLaP-Ainslie from ForWind Oldenburg, and FarmFlow from ECN. The reliabilities of the FLaP-Ainslie and the FarmFlow wind farm wake models are of equal order, and higher than FLaP-Jensen. Any difference between the predictions from these models is most clear in the double wake situation. Here FarmFlow slightly outperforms FLaP-Ainslie.

1 Introduction

Large wind farms suffer from wakes inside the farm, and, if present, from the wakes of neighboring wind farms. Offshore wind farms suffer even more due to the persistency of these wakes. This leads to poor prediction of the energy production in the development phase and energy losses during the operational phase. Overall, this results in disappointments for investors and operators. Accurate prediction has therefore been high on the priority list of R&D activities.

Energy research Centre of the Netherlands ECN and ForWind Oldenburg have specialized in this subject for more than ten years and in this paper present the latest results in the EU/FP7 project Cluster Design [1, 2]. Specifically the most advanced pragmatic and recently validated tools to predict the ambient conditions (WRF) and wind farm internal wakes (FarmFlow and FLaP) are revealed.

FarmFlow and FLaP have now been validated on flat terrain onshore wind farms and offshore wind farms. In this paper further validations on the offshore wind farm Alpha Ventus are addressed. Two cases are presented for inflow conditions originating from meteorological observations from the met mast FINO1, and meteorological simulations from the Weather Research and Forecasting model WRF. Additionally a single wake and a double wake situation are presented. First, section 2 presents the measurements, the modeling, and the assessment criteria. Next, the results of the comparisons between the measurements and the models are presented and discussed (section 3). Finally, section 4 presents the summary and conclusion.

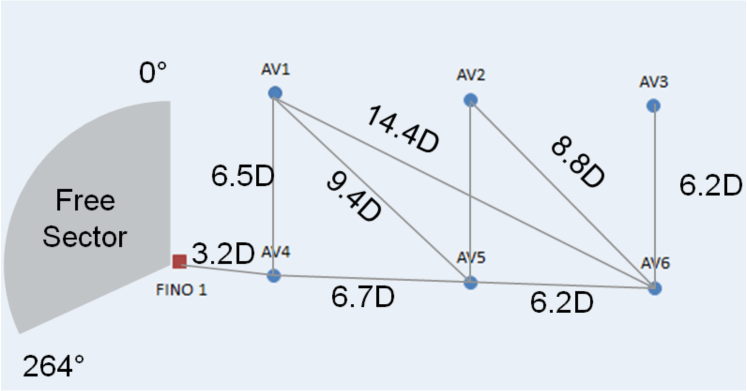

Figure 1. The wind turbines and the met mast considered in Alpha Ventus. Indicated are the positions of the REpower wind turbines and the FINO1 met mast, and the wind direction sector which is undisturbed from either the AREVA wind turbines (not shown) or the met mast. Distances are expressed in rotor diameters of 126 m

2 Methodology

2.1 Meteorological and wind turbine measurements

The wind farm Alpha Ventus is located at around 45 km to the north of the island Borkum. It consists of 12 turbines of the 5 MW class and a met mast, see figure 1. The six turbines in the north are REpower 5M with a hub height of 92 m and a rotor diameter of 126 m. The six turbines in the south (not displayed in figure 1) are AREVA Multibrid M5000. In the west, the predominant wind direction, there is the highly equipped met mast FINO1.

The time period from 23 March 2011 until 8 August 2012 was selected because sufficient measured data are available from the REpower turbines and the met mast. It should be noted that measured and any other data were not available from the AREVA turbines, so that these turbines and the wind direction sectors in their wind shadow had to be excluded from the analyses.

The results were saved in time series and in power matrices. The time series contain the wind conditions and the turbine powers at 10-minute time intervals. The power matrices contain two dimensions: one for the wind direction and the other for the wind speed. The models calculated their result for 1° wind directional sectors and in wind speed bins of 1 m/s. These results were arithmetically averaged to obtain further power matrices with wind direction sectors of 5°, 15° and 30°. Additional subsets were created by sampling on the turbulence intensity and/or the vertical wind shear.

2.2 The atmospheric modelling

The numerical simulation of the ambient atmospheric flow conditions was performed with the Weather Research and Forecasting (WRF) model. The simulated atmospheric conditions were subsequently fed to the wind farm wake models described in section 2.3.

The WRF model is a numerical weather prediction and atmospheric simulation system designed for both research and operational applications [3]. WRF solves the compressible, non-hydrostatic Euler equations in flux form. Its vertical coordinate is a terrain-following hydrostatic pressure coordinate, using a terrain-following mass vertical coordinate. The staggered Arakawa-C grid is used as a horizontal grid.

The numerical simulations were done with the WPS/WRF version 3.4.1 on the high performance cluster FLOW at Carl von Ossietzky University Oldenburg. The Intel FORTRAN compiler and the Intel MPI libraries were used.

For the simulation of the time series three two-way nested domains were defined. (See figure 2). The coarsest domain (domain 1) covers central and north-east Europe and has a horizontal resolution of $18 \times 18\,\mathrm{km}^2$. The grid ratio is as recommended 1:3. Therefore the other two domains have a horizontal resolution of 6 km and 2 km in both directions. The domains are centered over the location of the met mast FINO1. Each domain has 100 grid points in both horizontal directions and 62 vertical levels with a finer vertical resolution near the ground.

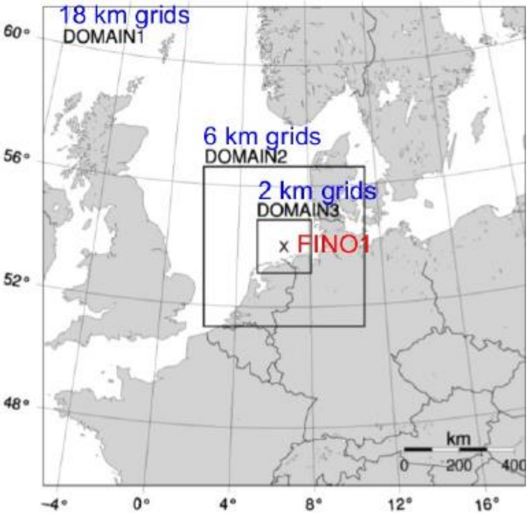

Figure 2. WRF domain sizes and grid resolutions with the offshore met mast FINO1 in the centre. The geographical grid uses a Lambert map projection with negligible projection errors at the location of FINO1

With full four-dimensional data assimilation in the first and second domain and also above level 33 (approximately 2 km above the planetary boundary layer) in the third domain the simulation were nudged to the reanalysis data which were used as input. The standard WRF nudging coefficients were used for this simulation.

Input data for the numerical simulations are the Climate Forecast System Reanalysis (CFSR) data from NCAR and Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA) data from MyOcean. The largest domain gets this data as boundary values every six hours for grid analysis nudging. The CFSR data has a horizontal resolution of about 38 km and 64 vertical levels. The OSTIA data were linearly interpolated from daily values and have a resolution of about 5 km.

2.3 The wake modelling

2.3.1 FarmFlow

FarmFlow uses a parabolized Navier-Stokes solver for the mean flow in combination with a kε sub-model for the turbulence, based on the UPMWAKE model [4, 5]. It employs a vortex-wake sub-model for the turbine near wakes [6, 7, 8], and profiles of the wind speed and the air temperature that are valid up to the heights where the multi-megawatt wind turbines operate [6, 7, 9, 10, 11, 12].

The computational domain of the ECNWake model in FarmFlow has the dimension of a rectangular box of 6.5 rotor diameters D in width and height, and a variable length. It contains a minimum of 96 equidistant grid cells in width and height directions both, and a minimum of 112 grid cells along the length. The grid in length-wise is stretched to resolve near wake effects. As a result, the rotor diameter has the dimension of 15 grid cells, and the rotor area is covered by approximately 175 grid cells. The step size in flow direction begins with $0.005D$ at the rotor area, and increases exponentially. After a distance of $20D$, the maximum step size of $1D$ is reached.

The dimensions of the computational domain are a compromise between acceptable calculation effort and necessary grid size for accurate results. Test calculations with grid refinement have shown that at least 13 nodes on the rotor diameter are necessary for accurate results. Other test calculations have shown that dimensions of at least 6 rotor diameters are necessary for accurate results when arrays with more than 20 turbines are modelled.

2.3.2 FLaP

2.3.2a Overview

FLaP is an engineering wake software that uses either the Jensen model or a modified Ainslie model to calculate the annual energy production of a cluster of wind turbines as well as the actual production by every single wind turbine at a given time step. It operates in either of two modes; one is driven with long-term wind statistics and employs a fixed value of the air density, whereas the other is driven with time series of wind speed and wind direction as well as air density and turbulence intensity.

2.3.2b FLaP-Jensen

The Jensen model implemented in FLaP is based on a single wake model developed by N.O. Jensen during the ninety eighties [13, 14]. The model takes into account the characteristics of the turbines, and is intended to be used for optimizing the cluster configuration for a given site, where the distribution of wind speeds and velocities are known.

The basic assumptions for the Jensen model are:

- Steady, incompressible and frictionless flow.
- Along the cross wind direction the wind velocity is constant inside the wake
- Neglecting of near-wake zone.
- Start diameter of wake is equal to rotor diameter.
- Wake diameter spreads linearly with increasing downstream distance.

The model is based on the balance of momentum. The wake deficit downstream of a single turbine depends on the distance behind the turbine, the velocity depending thrust coefficient, the wake decay coefficient, and the rotor diameter.

The wake decay coefficient is influenced by turbulence intensity and atmospheric stability [14, 15]. If the turbulence intensity is higher the turbulent mixing will be stronger and therefore the wake will spread wider. As a consequence the wake decay constant for higher turbulence intensities must be larger.

For calculation of whole wind farms the squares of the single wake deficits are superposed:

$$\left(1 - \frac{U_{n+1}}{U}\right)^2 = \sum_{i=1}^{n} \left(\frac{1 - \frac{U_{\mathrm{w},i-1}}{U}\sqrt{1 - C_\mathrm{T}}}{\left(1 + \frac{2kx}{D}\right)^2} \right)^2 \text{ with } U_{\mathrm{w},0} = U$$

where U_{n+1} is the wind speed at turbine $n+1$ with the number of wake deficits n which influences the upstream velocity of turbine $n+1$ and therefore are superposed, $U_{w,i-1}$ the wind speed upstream of a single turbine i.

It was found that this normalization and superposition are the reason for some misbehaviour of the FLaP-Jensen model in the case of multiple wakes. Further developments of the FLaP-Jensen model came along with improved superposition of single wakes:

$$(U - U_{n+1})^2 = \sum_{i=1}^{n} \left(U_{w,i-1} - U_{\mathrm{w},i}\right)^2 \text{ with } U_{\mathrm{w},0} = U$$

where $U_{w,i-1}$ is the velocity in the wake of the upstream turbine.

2.3.2c FLaP-Ainslie

The Ainslie model was developed by J. Ainslie in the ninety eighties [16], and was implemented by H-P Waldl ten years after [17]. It is like the Jensen model a static model and calculates single wakes which are afterwards superposed. Unlike the Jensen model the wake is described with a Gaussian profile.

The following assumptions were made for the Ainslie model [16, 17, 18]:

- Axisymmetric and fully turbulent wake.
- Stationary and incompressible flow without external forces.
- Ambient pressure gradients are neglected.
- Neglecting of near-wake zone.
- Gradients in radial direction are much larger than in axial direction.

To describe the flow field a system of equations consisting of the Navier-Stokes equation and continuity equation are necessary. Due to these assumptions the simplified two-dimensional Navier-Stokes equation plus the continuity equation in cylindrical coordinates are used. To close this system of equations an assumption for the Reynolds stress is employed. To this end the turbulent eddy viscosity approach is used [16]. The total eddy viscosity is assumed to be a superposition of ambient eddy viscosity of the atmospheric flow and the eddy viscosity generated by the wind shear in the wake of a turbine.

Since the Ainslie model is a single wake model the wakes are superposed for calculation of whole wind farms:

$$U_{n+1} = U_0 - \sqrt{\sum_{i=1}^{n} \frac{1}{A} \int_R \Delta_i \cdot |\Delta_i|} ,$$

where A is the rotor area and Δ_i the deficit in a single wake. The rotor generated *TI* is also superposed:

$$TI_{\mathrm{T}} = \sqrt{\sum_{i=1}^{n} \left(\frac{1}{A} \int_R TI_{\mathrm{w},i}^2 \right)} + TI_{\mathrm{a}}$$

where $TI_{w,i}$ is the rotor generated *TI* of a single wake and Ti_a the ambient *TI*.

2.4 Assessment criteria

2.4.1 Ambient conditions

If x_{obs} and x_{pred} indicate the observed and the predicted value of an ambient condition (either the wind speed WS, the wind direction WD, the turbulence intensity TI, or the vertical shear coefficient α), the following performance indicators are defined [19]:

1. Prediction error $\Delta_x \equiv x_{obs} - x_{pred}$, and
2. Prediction ratio $R_x \equiv x_{obs} / x_{pred}$.

On the basis of these performance indicators two tests are defined:

A. $-d_x \leq \Delta_x \leq +d_x$; the prediction error should be smaller than a pre-set value, and

B. $0.97 \leq R_x \leq 1.03$; the prediction should not differ more than 3% from the observation.

The values of d_x are 1 m/s (wind speed), 5° (wind direction), 1% (turbulence intensity), and 0.02 (shear coefficient).

2.4.2 Single and double wake situations

With m_{pow}, s_{pow} and N_{pow} the mean value, standard deviation and number of observation of the power of a wind turbine in a given wind direction sector, the experimental error E_{pow} is defined by

$$E_{pow} = f_{N_{pow}} \frac{s_{pow}}{\sqrt{N_{pow}}} ,$$

where f_{Npow} is Student's t-factor for the N_{pow} observations in the sector and, in this case, a probability of 97.5%. (The Student t-factor is a parameter used to test the hypothesis that a random sample of normally distributed observations has a given mean.)

If P_{pred} indicates the power predicted by a wind farm wake model, either FLaP-Jensen, FLaP-Ainslie or FarmFlow, the prediction error Δ_{pow} is defined by [19]

$$\Delta_{pow} \equiv m_{pow} - P_{pred} .$$

By using m_{pow}, E_{pow}, Δ_{pow}, P_{pred} and the nominal turbine power P_{nom}, three performance indicators and associated tests are defined:

1. $-1 \leq \frac{\Delta_{pow}}{E_{pow}} \leq +1$; the prediction error should not be greater than the experimental error.
2. $-0.03 \leq \frac{\Delta_{pow}}{P_{nom}} \leq +0.03$; the prediction error should be smaller than 3% of the turbine nominal power.
3. $0.97 \leq \frac{P_{pred}}{m_{pow}} \leq 1.03$; the predicted value should not differ more than 3% from the observed value.

The performance indicators are presented as a function of the wind direction. The outcome of these tests is presented as the fraction of the predictions that pass.

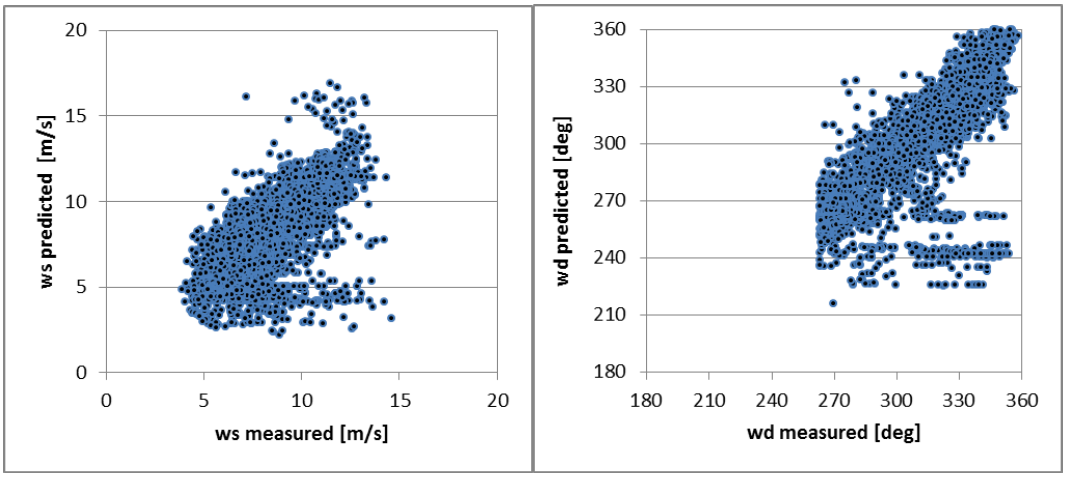

Figure 3. Correlation between the observed and the predicted ambient wind speed (left) and ambient wind direction (right)

Table 1. Percentage of predictions that passed the tests on the wind conditions

Quantity	**Test A**	**Test B**
Wind speed	53.4	14.2
Wind direction	35.2	NA
Turbulence intensity	25.4	0.0
Vertical shear coefficient	9.6	0.0

3 Results

3.1 Ambient conditions

In this section the predicted ambient conditions of the Alpha Ventus wind farm are compared to the observed ambient wind conditions on a point to point basis. The predictions originate from the atmospheric model WRF (see section 2.2) and the observations originate from the FINO1 met mast (see section 2.1). The ambient conditions comprise the wind speed WS, the wind direction WD, the turbulence intensity TI, and the vertical shear coefficient α.

In this section the performance of the atmospheric model is presented. The figure 3 shows the correlation between observed and predicted 10-minute values. And table 1 presents the percentages of predictions that passed the tests. Recall that the comparison is limited to the wind directions between 264° and 360°, see figure 1.

3.2 Single wake situation

In this section the performance of the three wind farm wake models as fed with simulated atmospheric data is tested for the situation where the wind turbine AV5 is in the wake of the wind turbine AV4. (See figure 1). This situation occurs if the wind direction is near 270°. In the evaluation power matrices with wind direction sectors of varying widths are compared, as indicated in section 2.1: 1°, 5°, 15° and 30°. Further, although not all wake models could handle this, turbulence intensities of 2%, 5%, 8% and 11% are considered.

The performance of the wind farm design models is presented in two different ways, namely for:

1. The given wind speed of 11 m/s in combination with different wind directions in the range between 270° and 360°, and
2. Different wind speeds between 3 m/s and 14 m/s in combination with the given wind direction of 270°.

In both cases the turbulence intensity is 8%. Recall wind directions between 270° and 360° are the interval where the REpower turbines are not disturbed by either the AREVA turbines or the met mast.

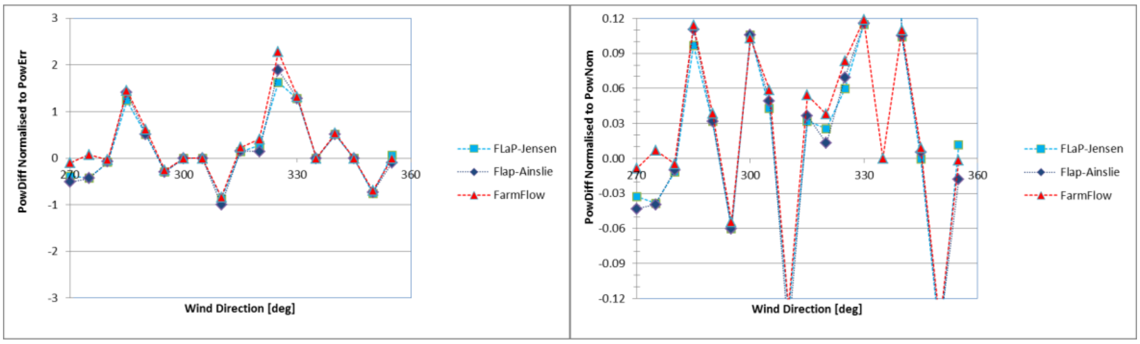

Figure 4. Ratio of the prediction error Δ_{pow} and the experimental error E_{pow} (left) or the nominal turbine power P_{nom} (right); single wake AV5, wind speed 11 m/s, turbulence intensity 8%

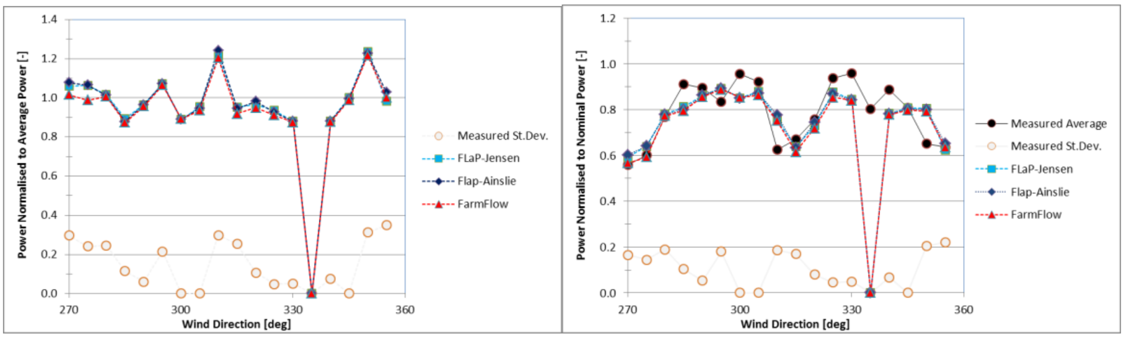

Figure 5. Ratio of the predicted power P_{pred} and the observed power m_{pow} (left) or the nominal power P_{nom} (right); single wake AV5, wind speed 11 m/s, turbulence intensity 8%. Also shown is the ratio of the standard deviation and average value of the observed power

Table 2. Percentage of predictions that passed the tests; single wake AV5, wind speed 11 m/s, turbulence intensity 8%; sector width 5°

	FLaP-Jensen	**FLaP-Ainslie**	**FarmFlow**
Test 1	73.3	73.3	73.3
Test 2	21.1	21.1	27.8
Test 3	15.8	21.1	27.8

First the performance is presented for a wind speed of 11 m/s and a turbulence intensity of 8%. The performance indicators are shown in the figures 4 and 5; the wind direction sector size is 5°. Table 2 presents for different sector widths the corresponding percentages of predictions that passed the tests. Figure 5 also presents power values as normalised to the nominal power.

Next the performance is presented for a wind direction of 270° and a turbulence intensity of 8%. The wind direction sector size is 5°. The results are shown in the figures 6 and 7, and in table 3.

3.3 Double wake situation

In this section the performance of the three wind farm wake models as fed with simulated atmospheric data is tested for the situation where the wind turbine AV6 is in the wake of the wind turbines AV4 and AV5. (See figure 1). This situation occurs if the wind direction is near 270°. The assessment method is the same as for the single wake case in section 3.2.

The figures 8 and 9, and table 4, present the results for a wind speed of 11 m/s and a turbulence intensity of 8%. For a wind direction of 270° and a turbulence intensity of 8%, the results are shown in the figures 10 and 11, and table 5.

3.4 Discussion

In contrast to the statistical values, in general the predictability of point values of the ambient conditions is poor. May the predictability of the wind speed and the wind direction be reasonable if sufficiently sized tolerances are employed, it is fairly impossible to predict the turbulence intensity and the vertical shear. This is caused by inherent limitations of the atmospheric model

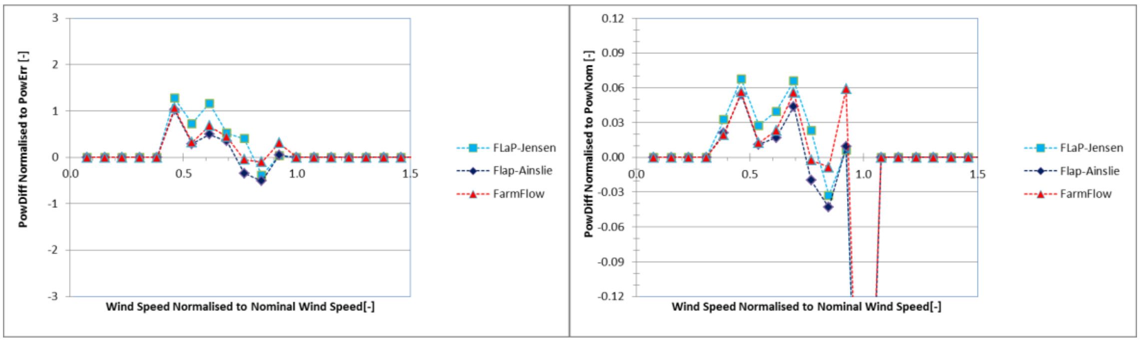

Figure 6. Ratio of the prediction error Δ_{pow} and the experimental error E_{pow} (left) or the nominal turbine power P_{nom} (right); single wake AV5, wind direction 270°, turbulence intensity 8%

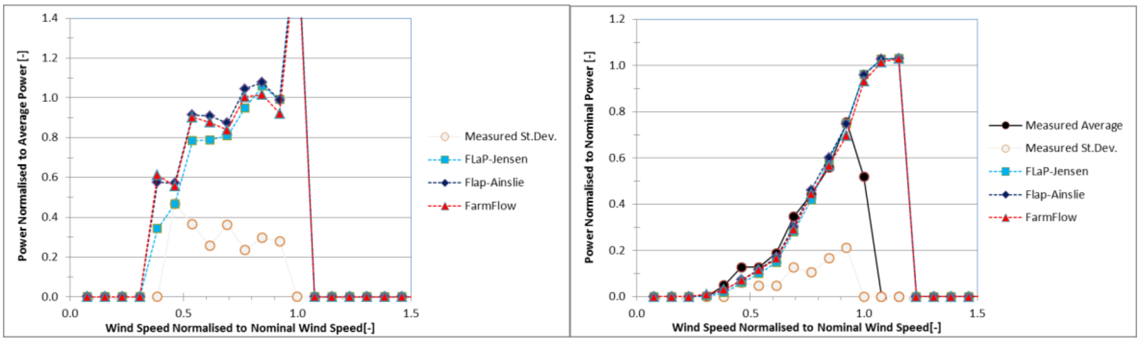

Figure 7. Ratio of the predicted power P_{pred} and the observed power m_{pow} (left) or the nominal power P_{nom} (right); single wake AV5, wind direction 270°, turbulence intensity 8%

Table 3. Percentage of predictions that passed the tests; single wake AV5, wind direction 270°, turbulence intensity 8%; sector width 5°

	FLaP-Jensen	FLaP-Ainslie	FarmFlow
Test 1	71.4	85.7	85.7
Test 2	71.4	81.4	55.6
Test 3	11.1	11.1	22.2

(not specifically WRF), where the sub-model for the turbulence is to produce reliable values of the Reynolds-averaged wind speed and not the tensor with Reynolds stresses itself, and it is assumed that a logarithmically shaped wind profile occurs in the lowest hundred meter of the atmospheric boundary layer.

If the experimental uncertainty were the sole criterion for the power, the three wind farm wake models deliver reliable predictions for the single and the double wake situations. The reliability however is lower for the double wake situation as compared with the single wake situation. If on the other hand the criterion is based on operational data, either the nominal power or the actual power, the reliability is much lower.

In general the reliability of the FLaP-Ainslie and the FarmFlow wind farm wake models is of the same order, and higher than FLaP-Jensen. This can be understood from the more advanced character of the CFD-based FLaP-Ainslie and FarmFlow models as compared to the analytical FLaP-Jensen model. Any difference between the predictions from these models are most clear in the double wake situation. Here FarmFlow slightly outperforms FLaP-Ainslie because of the more advanced turbulence sub-modelling.

4 Summary and conclusion

In this paper the ability is demonstrated to make wind farm wake calculations on the basis of ambient conditions that were calculated with an atmospheric model.

Specifically, this paper describes the results of the comparison between the predicted and the observed ambient conditions, and the comparison between power predictions from three wind farm wake models for a single and a double wake situation.

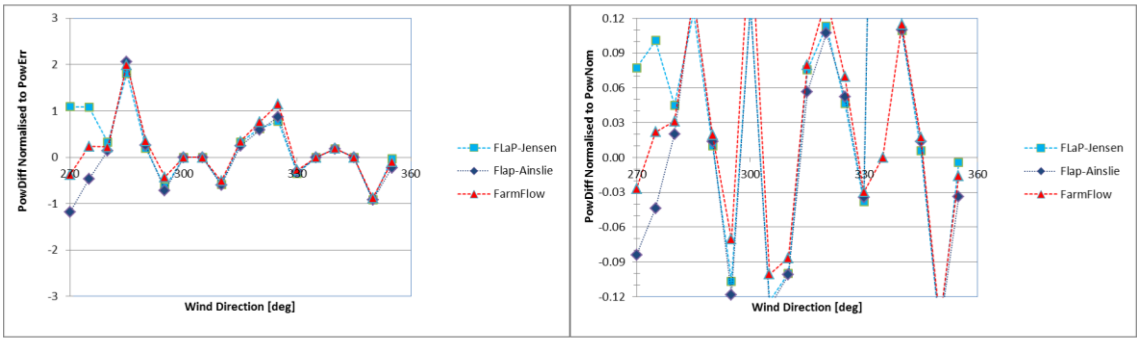

Figure 8. As figure 4 but double wake AV6

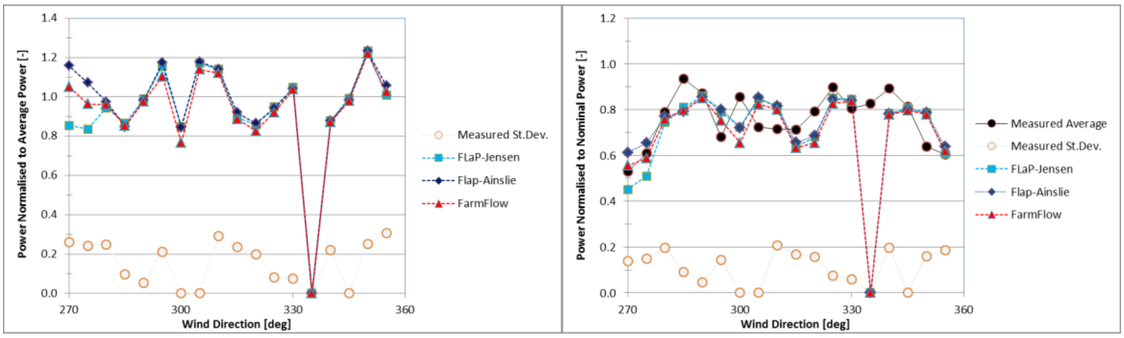

Figure 9. As figure 5, but double wake AV6

Table 4. As table 2, but double wake AV6

	FLaP-Jensen	**FLaP-Ainslie**	**FarmFlow**
Test 1	73.3	86.7	86.7
Test 2	15.8	15.8	33.3
Test 3	15.8	15.8	16.7

The comparisons between the observations and the predictions are based on performance indicators and test criteria, with the objective to determine the percentage of predictions that fall within a given range about the observed value. The performance indicators are based on either the difference or the ratio of the observed and the predicted value. Test criteria for the ambient conditions and the power were defined. Those for the power employ the experimental uncertainty, a percentage of the nominal power, or a percentage of the observed power.

The Alpha Ventus site was considered. It consists of a wind farm with the same name and the met mast FINO1. Data from the 6 REpower wind turbines and the FINO1 met mast were employed to compare the observations with the predictions.

The atmospheric model WRF was used in order to predict the ambient conditions at the location and the measurement heights of the FINO1 mast.

In order to predict the individual turbine powers three wind farm wake models were employed: FLaP-Jensen and FLaP-Ainslie from ForWind Oldenburg, and FarmFlow from ECN.

The comparison between the predictions and the observations was performed for the wind directions where the REpower turbines and the FINO1 met mast are free from disturbances from either the AREVA turbines or the met mast. Almost 17 months of 10-minute averaged data were available for the analysis.

May the atmospheric model predict the wind speed and the wind direction reasonably, it is fairly impossible to predict the ambient turbulence intensity and vertical shear. The reliabilities of the FLaP-Ainslie and FarmFlow wind farm wake models are of equal order, and higher than FLaP-Jensen. Any difference between predictions from these models are most clear in the double wake situation. Here FarmFlow slightly outperforms FLaP-Ainslie.

Acknowledgements

The projectFP7-Energy-2011-1 283145 / ClusterDesign is co-funded by the EC.

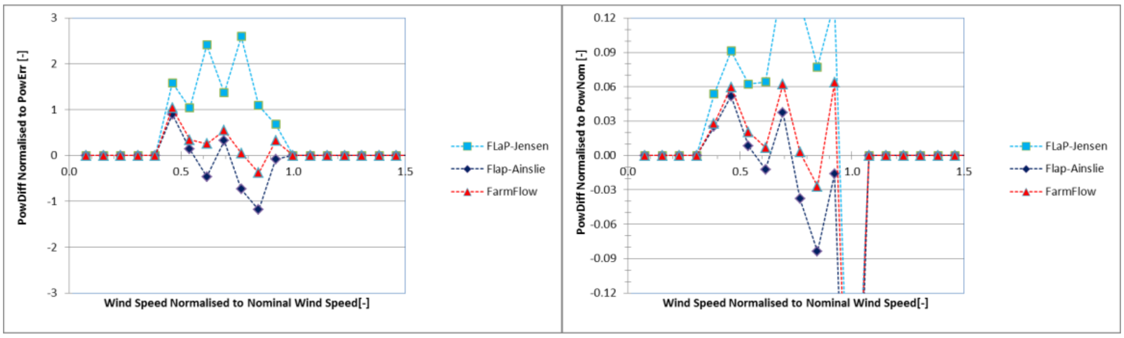

Figure 10. As figure 6, but double wake AV6

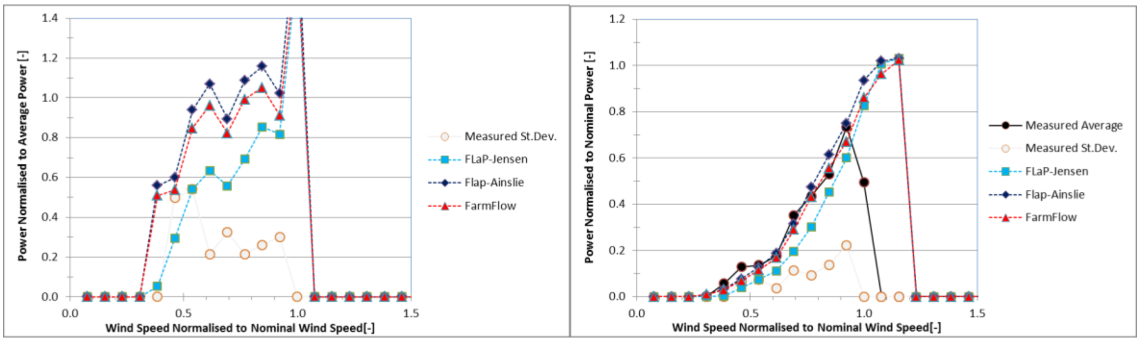

Figure 11. As figure 7, but double wake AV6

Table 5. As table 3, but double wake AV6

	FLaP-Jensen	**FLaP-Ainslie**	**FarmFlow**
Test 1	14.3	85.7	85.7
Test 2	57.1	76.2	55.6
Test 3	0.0	11.1	11.1

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